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Programmable Turbidistat for Suspended Particles in Laboratory Aquaria

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A PROGRAMMABLE TURBIDISTAT FOR SUSPENDED PARTICLES IN LABORATORY AQUARIA[1]

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Abstract: A system for precise control of suspended particle concentrations in laboratory aquaria is described. It comprises an air-lift dosing system, a transmissometer to measure particle concentration, and a microcomputer which calculates the dose required to achieve a programmed turbidity.

INTRODUCTION

There is an increasing need for laboratory exposure systems to study the effects of suspended particles introduced into the marine environment by ocean disposal operations. It is desirable, for example, to predict the potential results of dumping sewage sludge or dredge spoil in coastal waters. We have developed a laboratory bioassay system for use with *Mytilus edulis* L. which is capable of maintaining well-defined concentrations of suspended materials for extended periods of time, regardless of changes in the grazing or filtration rate of the experimental organisms. The system is an enhancement of a basic control-system configuration used by Winter (1973) to feed bivalves microalgae. Winter's system comprised a controllable dosing valve, a colorimeter to measure particle concentration, and a simple electronic control circuit. Other investigators (Rissgard & Mohlenberg, 1979; Botter-Jensen & Dahlgaard, 1981; Janssen & Dreyer, 1981) have modified Winter's design by using controlled pumps rather than valves, and specially constructed turbidity-measurement systems to provide better sensitivity and stability. However, no substantial improvements to Winter's electronic control circuitry have been described; all the systems require careful manual adjustment and stable conditions to maintain accurate control.

Controlling sediment suspensions in the laboratory is a more complex problem than controlling microalgae since sediment particles have such a wide range of densities and sizes. Peddicord & MacFarland (1978) have used paddlewheels, and Rubenstein & Wilkes (1980) have used solenoid valves to deliver sediments to experimental systems. However, accurate long-term control was not achieved due to sediment accumulation in the delivery apparatus. These workers did not employ continuous monitoring systems to detect and compensate for drift.

[1] Contribution No. 266 of the U.S. EPA Environmental Research Laboratory, Narragansett.

We have modified Winter's system for use with suspended sediments by incorporating a new air-lift delivery apparatus which is free from sedimentation problems, and by using a programmable microcomputer control system. With the microcomputer, manual adjustments are unnecessary as conditions change (for example, when a new batch of sediment slurry is placed in the delivery reservoir). The microcomputer calculates the volume for each pulse of delivered sediment based not only on the desired turbidity (the setpoint) and the measured turbidity, but also on the magnitude of previously delivered pulses. Further, the microcomputer can be programmed to vary the setpoint according to a desired pattern of turbidity changes such as may occur with tidal currents or episodic discharges from land or industrial and municipal outfalls.

System Description

OVERVIEW

The system configuration (Fig. 1) shows the reservoir of suspended sediment slurry (SL) at the left, with an air-lift delivery line (DL) and a separate sea-water (SW) line

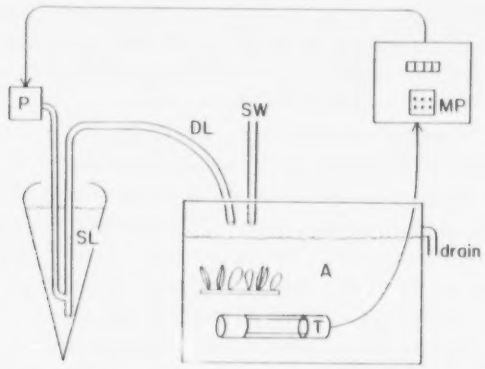

Fig. 1. Diagram of experimental setup: sea-water–sediment slurry (SL) in separatory funnel is delivered to the experimental aquarium (A) through delivery tube (DL); sea water (SW) flows continuously into the aquarium at $\approx 2\,l \cdot min^{-1}$; transmissometer (T) measures actual sediment concentration; microcomputer (or microprocessor, MP) controls air pump (P), delivering sea-water–sediment slurry to the aquarium as required to maintain sediment concentration at a desired setpoint; not shown are aeration lines to maintain uniform mixtures and prevent settling in both separatory funnel and aquarium.

entering the experimental aquarium (A). Air bubblers (not shown) vigorously mix both the slurry reservoir and the aquarium to ensure uniform dispersion of the particles. In the aquarium, sediment will be removed from suspension primarily by the grazing activity of *M. edulis*, sedimentation, and flow out the drain. The particle concentration in the aquarium is measured by a transmissometer (T). The microcomputer (MP)

calculates an appropriate sediment delivery rate based on this measurement and turns the air pump (P) on and off at intervals to achieve this delivery rate.

AIR-LIFT DOSING SYSTEM

Air bubbling through the delivery tube (DL) carries slurry with it into the experimental aquarium. The vigorous bubbling motion ensures that the slurry is delivered without sedimentation or sorting which could modify its characteristics.

The delivered sediment dose may be defined as the slurry concentration multiplied by the pumping time and the volume delivery rate. The volume delivery rate is a function of the peak height of the delivery tube above the slurry, the depth of the tube in the slurry, the air pressure, and many mechanical construction details. A typical setup might use a polypropylene tube of 3–6 mm i.d., 30 to 50 cm long bent into an inverted "J". Air from a Silent Giant[1] or similar pump is introduced at 2–4 cm above the bottom of the tube in the slurry. Actual dimensions vary depending on dosing requirements. Experiments show that the volume delivery rate of a particular system will be quite repeatable as long as the slurry is maintained at a constant level. Table I shows average

TABLE I

Performance of the air-lift dosing apparatus, expressed as delivered volume and standard deviation at selected pulse durations.

Number of trials	Pulse duration (s)	Average volume delivered (ml)
20	2.5	8.76 ± 0.42
22	5.0	19.27 ± 0.55
22	10.0	36.18 ± 0.66

delivery volumes and standard deviations measured on a prototype system as a function of pumping times.

As slurry is depleted, the volume delivery rate decreases slowly and uniformly; the microcomputer calculations required to compensate for this type of change are easily programmed. This problem also may be corrected by using a dual-reservoir system in which slurry from a main reservoir is continuously pumped into the dosing reservoir, while an overflow from the dosing reservoir returns excess slurry to the main reservoir. This maintains a constant level in the dosing reservoir until the main one is entirely depleted.

[1] Mention of any commercial product in this article does not imply endorsement by the Environmental Protection Agency.

PARTICLE CONCENTRATION MEASUREMENT

An accurate, stable measurement of particle concentration is crucial to proper operation of the system. The microcomputer can be programmed to compensate automatically for variations in slurry delivery or bivalve grazing, but no algorithm has been found to measure or compensate for an incorrect particle measurement. A transmissometer (T) placed directly in the experimental aquarium will measure suspended particle concentration accurately and continuously. Transmissometers conform well to a simple exponential equation ($I = I_0 e^{-Kc}$), relating particle concentration (c) to measured transmission (I) and constants I_0 (clear-water transmission), e (base of the natural logarithms), and K (a constant incorporating path length and other factors). We have used transmissometers manufactured by Sea Tech, Inc.; the charts in Figs. 2–4 are derived from a unit with a 25-cm path length. A 10-cm transmissometer also has been used, as its sensitivity is well matched to our desired experimental particle concentrations. Both of these units are reported to be very stable and immune to interference by ambient light (Bartz *et al.*, 1978).

MICROCOMPUTER CONTROLLER

The eight-bit microcomputer used for this work was assembled in-house from standard electronic components. A keypad and eight-digit display are provided for the experimenter to control and monitor the equipment. Inexpensive eight-bit analog-to-digital conversion for the transmissometer signal provides a measurement resolution of one part in 255, which is more than adequate for this work. There are eight digital outputs, allowing this microcomputer to control particle concentrations in up to eight separate tanks simultaneously. The computer's operating instructions and certain invariant data (such as a sine table) are fixed permanently in 4096 bytes of Read-Only Memory, while variable parameters (such as setpoint, gain and actual turbidity for each tank) are stored in 1024 bytes of read/write memory. Commercial circuit boards may be purchased with the hardware described for under $1000 (1982 prices), depending on the level of electronic expertise available locally to specify and interconnect the boards and components. Contact the senior author for specific design information and a program listing.

CONTROL ALGORITHM

The primary reason for using a microcomputer in the control circuitry is to improve the control algorithm. Previous workers in this field used a technique similar to a household thermostat, in which the controlled parameter oscillates between a lower (turn-on) limit and an upper (turn-off) limit. The difference between these limits might be as small as 2% (Winter, 1973), but with this control technique the actual turbidity variations often may be considerably larger than the on/off limits would seem to indicate. These workers found that their equipment was not easily set up for a desired

particle concentration, and the actual concentration would change as removal rates changed or the concentration of the stock algal suspension changed.

The control algorithm programmed into our microcomputer may be compared to the technique used by a person who drives his car at a constant speed over hilly roads. The driver continually compares his actual speed with his desired speed and corrects the position of the car's throttle to maintain a zero error. He does this by making small changes to the throttle setting based on his perceived need for more or less power than the previous setting. Our system takes measurements at defined intervals (such as once every 2 min), and at each interval calculates an appropriate pumping time (often in the range of 0.1 to 5.0 s, but it may be up to 25.5 s maximum) to deliver sediment slurry to the aquarium. Corrections to this pumping time are based on both present error and past accumulated errors. In the microcomputer program this algorithm is expressed mathematically as

$$B_n = B_{n-1} + (G_I \cdot E) \tag{1}$$

$$D = B_n + (G_p \cdot E) \tag{2}$$

The term B_{n-1} represents the "base", or remembered dosing rate at the last sample time; B_n represents the new "base" rate (which will be further modified by Equation (2) before an actual pulse duration is derived). G_I is the "integrator" gain and E is the error (setpoint minus measured particle concentration). Mathematically, Equation (1) would be an integral if the time intervals between sample times were infinitesimal. The term D represents the actual dose calculated for the present sample time, which depends on both the integrated error B_n, and the present error multiplied by proportional gain G_p. The primary benefit of this algorithm is that under stable conditions in the tank and dosing apparatus, the error term (E) will eventually be reduced to zero and the dose (D) will equal the base (B_n). It is not necessary for the operator to program the microcomputer with the sediment slurry concentration, slurry depth in the dosing reservoir, number of organisms in the tank, or diluent sea-water flow; nor is it necessary for the actual turbidity in the tank to oscillate from the low to high limit for the system to work. With proper choice of gain factors for the integrator and proportional terms in the equation, response to changing conditions will be rapid and precise. The principles underlying this algorithm, and the conditions under which it is stable, may be found in Shinskey (1967) or other texts on process-control systems.

As presently programmed, the microcomputer may be instructed to use a constant setpoint, or the setpoint may be derived from a sine table. With an appropriate choice of time constants, this can simulate a tidal cycle. Other desired patterns can be incorporated as needed.

SYSTEM PERFORMANCE

Tests were run to document system behavior over short, medium and long time intervals. In each case, theoretical predictions were confirmed by actual measurement.

The system was assembled as in Fig. 1, using an aquarium (A) containing 67 l of sea water. The stock sediment slurry was prepared by adding 40 ml of a homogeneous sediment to each liter of sea water in the reservoir (SL). Sediment concentration in the aquarium was monitored by a 25-cm transmissometer (T), recorded continuously on a chart recorder, and confirmed by weighing samples of filtered sediment collected at varying intervals. The microcomputer (MP) was adjusted to take a measurement and deliver sediment to the aquarium every two minutes. There were no filter-feeding organisms in the tank, but sediment was lost from the water column by sedimentation and overflow to the drain as sea water (SW) flowed through the aquarium at 2 l · min $^{-1}$.

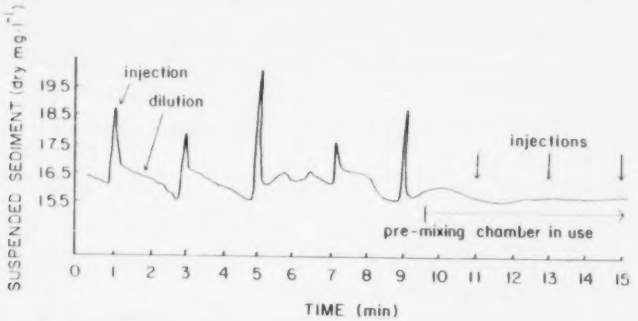

Fig. 2. Recording of transmissometer signal, calibrated to show changes in suspended sediment concentration over time in an aquarium with the microcomputer-controlled dosing system in operation: sharp peaks at each injection of sediment–sea-water slurry were caused by plumes of concentrated sediment which crossed the optical path of the transmissometer before mixing was complete; the slope of the line after the peak agrees with theoretical prediction of the rate of change of sediment concentration due to dilution by influent sea water; after 10 min a 2-l premixing dish was placed in the aquarium to receive both sediment doses and dilution sea water, eliminating concentrated injection plumes in the main aquarium.

Fig. 2. shows short-term performance with the setpoint adjusted to 15.5 mg · l $^{-1}$. The sediment additions did not immediately mix completely with the water in the aquarium, but first formed plumes which drifted into the light path of the transmissometer causing the sharp peaks in the recording. However, within a few seconds the mixture in the aquarium became homogeneous; this mixing period was followed by a steady decline in concentration as particles were removed by overflow and sedimentation. The rate of this decline agrees with the theoretical removal rate (2 l · min $^{-1}$ × 15.5 mg · l $^{-1}$ × 2 min = 62 mg of sediment per cycle, or ≈ 1 mg removed from each liter in the aquarium, which agrees with the recording).

To mitigate the influence of the short-term mixing phenomenon, a premixing chamber was added in the aquarium. It was a 2-l dish placed to receive both the sediment additions and the influent sea water; this almost perfectly damped the short-term fluctuations (Fig. 2).

A classical test for accuracy and stability of a feedback loop, such as the one employed here, is the imposition of a large acute change in any of the conditions which

ultimately affect the output (i.e. dosing rate). Fig. 3 shows the response of our system when the setpoint was changed from 4.7 mg·l^{-1} to 17 mg·l^{-1}. Response was quick and accurate, with only small overshoot.

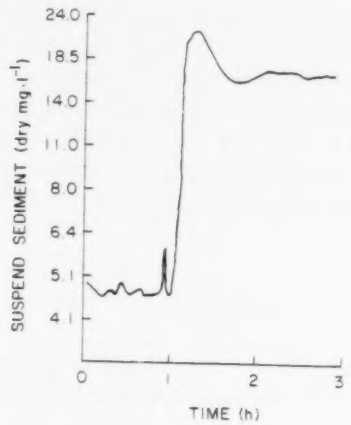

Fig. 3. Concentration of suspended sediment measured by transmissometer during a large change in setpoint: at ≈ 1 h on this recording, the setpoint was changed from 5 mg·l^{-1} to 15 mg·l^{-1}; the concentration reached a peak value of ≈ 20 mg·l^{-1}, but converged smoothly and quickly to the correct value.

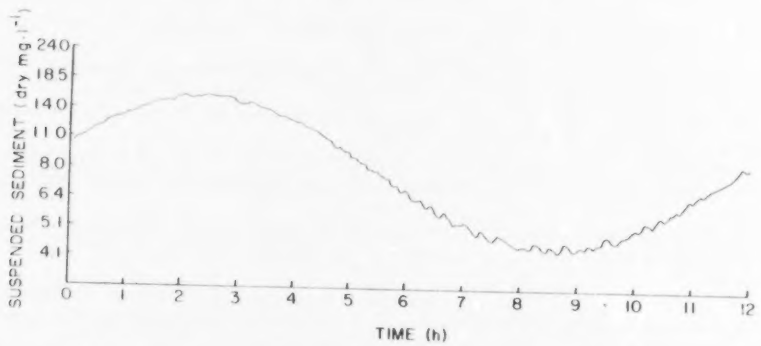

Fig. 4. Suspended sediment concentration measured by transmissometer during part of a microcomputer controlled tidal cycle simulation.

Finally, the system was set to simulate turbidity conditions over a tidal cycle (Fig. 4). The overall shape of the curve was faithful to the programmed variation and excellent replication of peak turbidity was observed. The noise evident in lower turbidity ranges (e.g. <6.4 mg·l^{-1}) was expected, and demonstrates two phenomena: (1) the gain factors in Equations (1) and (2) were not optimum for these low concentrations (having been set for the region of 16 mg·l^{-1} and (2) the stock slurry was so concentrated that

the shortest possible dosing pulses of 0.1 s delivered an excess of sediment relative to actual requirements. If the desired steady-state concentrations had been in the range of 5 $mg \cdot l^{-1}$, the gain and slurry concentration could have been adjusted easily for optimum control there.

This system, equipped with a 10-cm transmissometer, has been used over a period of 40 days for studies with *M. edulis*. Turbidity has been maintained within desired tolerances while the system was unattended over weekends. Once the influent sea-water supply failed and the microcomputer shut off sediment dosing entirely, maintaining the desired setpoint almost exactly. We anticipate employing this system for studies with pelagic filter-feeding organisms as well as benthic species. The system should also be useful in modeling chemical and physical transport of sediments or other suspensions of fine particles.

Acknowledgements

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